

Compressive behavior of double-tube concrete columns with an outer square FRP tube and an inner circular high-strength steel tube

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HIGHLIGHTS

- Hybrid DTCCs with an HSS tube possess excellent load-carrying capacity and axial deformation capacity.
- Local buckling of the HSS tube in a DTCC can be effectively restrained.
- Interaction between the HSS tube and the FRP-confined concrete leads to some benefits.
- Inner HSS tube not only resists axial load, but also provides further confinement to the concrete.

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ABSTRACT

Double-tube concrete columns (DTCCs) are a novel form of hybrid columns which consist of an outer fiber-reinforced polymer (FRP) tube, an inner circular high-strength steel (HSS) tube and the concrete filled in the entire section. In a DTCC, the inner HSS tube not only effectively diminishes the non-uniformity of stress distribution of concrete in a concrete-filled square FRP tube but also enhances the confinement to the core concrete, with its buckling being effectively restrained by the surrounding concrete and the outer FRP tube. This paper presents the results of an experimental study on the axial compressive behavior of DTCCs with an outer square FRP tube. Eight square DTCC specimens were tested under axial compression. The examined column parameters included FRP tube thickness, FRP tube width, and FRP type. The experimental results show that, in square DTCCs, the concrete is well confined by both the FRP tube and the HSS tube, and the buckling of HSS tube is effectively restrained so that its high material strength can be effectively utilized, leading to an excellent column performance. The experimental results also demonstrate that square DTCCs possess considerable post peak strength, indicating excellent ductility and promising application potential of this new form of hybrid column members in earthquake prone zones.

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1. Introduction

Fiber-reinforced polymer (FRP) composites have been increasingly employed in civil engineering applications, both in the upgrading existing structures and in new constructions. Due to their high strength-to-weight ratio, excellent corrosion resistance and tailorability in mechanical properties, a particularly popular and promising application of FRP composites is strengthening of reinforced concrete (RC) columns in the form of an external FRP jacket or FRP tube. In this respect, the fibers in an FRP jacket or an FRP tube are predominantly in the hoop/transverse direction

for providing lateral confinement to the inner concrete. Owing to the confinement provided by the FRP composites, both the compressive strength and ductility of the concrete can be substantially increased [2–14].

Many efforts have also been made to incorporate FRP in new constructions, aiming at excellent durable structures that only need minimal maintenance. Concrete-filled FRP tubes (CFFTs) (Fig. 1a) are probably the most popular type of hybrid members made of concrete and FRP. For new constructions, prefabricated FRP tubes are preferred, as they can serve as the formwork for casting concrete [16,15]. When a CFFT is under axial compression, the concrete core is subjected to lateral confinement exerted by the FRP tube, leading to tri-axial compressive stresses in the concrete; the FRP tube is consequently subjected to hoop tension. Since FRP

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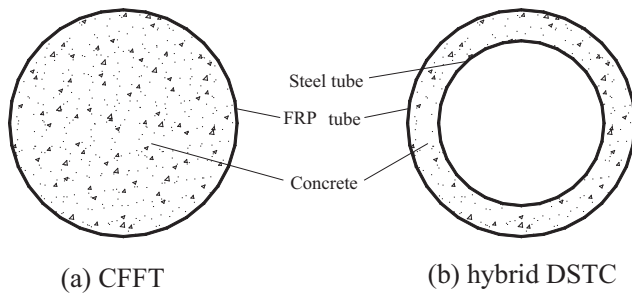


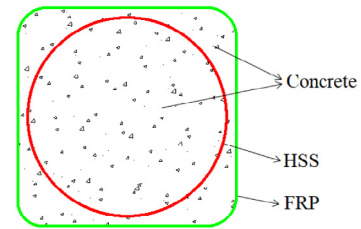
Fig. 1. Typical cross-sections of CFFTs and hybrid DSTCs.

behaves almost linear-elastically, the lateral confinement on the concrete core increases continuously with the lateral dilation of concrete. As a result, both the strength and ductility of the concrete core can be greatly enhanced. However, for CFFTs with a square/rectangular FRP tube, the confinement efficiency is much lower than that of concrete in circular columns because of the non-uniform FRP confinement resulting from the flat sides and sharp corners [17–19]; however, square/rectangular columns are more commonly utilized in practice.

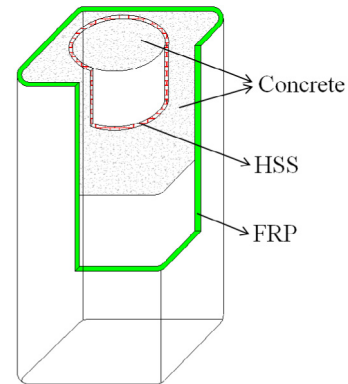
FRP tubes are also effectively employed for hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) proposed by Teng et al. [15]. The DSTCs consist of an inner steel tube, an outer FRP tube and the concrete filled in between (Fig. 1b). The novel combination of the three materials in a structural member is expected to possess some advantages such as the ability to support construction load due to the presence of a stiff/strong inner steel tube and diminution of seismic attack on account of the annular section [15]. This new column form has received further research interests (e.g., [20–28,35]). However, in a DSTC, the inner steel tube is prone to buckle inwardly due to the void at the center, leading to an insufficient utilization of the strength of the steel.

On the other hand, a number of studies (e.g., [29,30]) have been conducted on the structural use of high-strength steel (HSS) products, but its use has so far been rather limited. One of the restrictions for an extensive use of HSS is the greater susceptibility of HSS members to buckling failures compared to normal-strength steel members. Such buckling failure should be avoided in structures as it portends that the yield strength of HSS cannot be fully utilized and the ductility of the structural member can be greatly compromised [31,32]. Note that ductility is of great significance to prevent the progressive collapse of structures, subsequently reducing loss of lives and properties during earthquakes. Additionally, for axially loaded concrete encased steel columns, the yield stress of steel is not expected to be higher than 500 MPa as the concrete would experience crushing failure at a strain of around 0.0020–0.0035 at which the strength of HSS (especially the post-yield strength) is not fully exploited yet. To avoid this problem, it is reasonable to utilize HSS in FRP-confined concrete which has a much higher ultimate compressive strain than that of plain concrete.

Against this background, a novel form of hybrid columns, FRP-concrete-steel double-tube concrete columns (DTCCs) (Fig. 2) with an outer square FRP tube and an inner circular HSS tube, is proposed in this study to address the above concerns. A hybrid square DTCC consists of three parts: an outer square tube made of FRP, an inner circular tube made of steel and the in-filled concrete in all the space inside the two tubes. Compared with FRP-confined concrete columns, the new hybrid columns are expected to have higher enhancements in both strength and ductility. In a square DTCC, part of the concrete near the flat sides of the column section where the confinement from the FRP tube is not sufficient is replaced by steel. The inner steel tube is expected to possess a diameter slightly



(a) Typical cross-sections of a square DTCC



(b) Three-dimensional schematic diagram of a square DTCC

Fig. 2. Cross-sections and three-dimensional schematic diagram of a square DTCC.

smaller than the internal width of the outer FRP tube; in such a case, the weakly confined concrete near the flat sides of the column is further confined by the inner circular steel tube while the gap between the outer FRP tube and inner steel tube can be easily filled with concrete (Fig. 3). The concrete performance is thus expected to be better than that in a square CFFT. Both the inward and outward buckling of the steel tube are restrained by the surrounding concrete; and the concrete is further confined by the outer FRP tube. The combination of materials is expected to lead to a corrosion-resistant and labor-saving column: the steel tube and FRP tube serve as the in-situ formwork which significantly reduces the cost of labor and formwork. The inner steel tube is protected by the outer FRP tube from being deteriorated as the FRP possesses high corrosion resistance. The DTCCs also allow the effective utilization of the yield strength of HSS. The DTCCs are expected to be utilized particularly as supporting members of high-rise buildings or infrastructures in earthquake prone zones due to their expected excellent strength and ductility. Existing test results [33] have demonstrated that circular DTCCs with an HSS tube process excellent ductility as the local buckling of the HSS tube was effectively prevented and the concrete was well confined. It should be noted that hybrid DTCCs with an outer circular FRP tube and an inner circular HSS tube is an emerged hybrid column form proposed by Teng and Yu [33] for the first time and has been demonstrated to have excellent performance by Teng et al. [34]; however, the compressive behavior of square DTCCs with an HSS tube has never been studied thus far.

This paper presents the results of an experimental study that included ten hybrid DTCCs with an outer square FRP tube and an inner circular HSS tube. For ease of discussion, the hybrid DTCCs with an outer square FRP tube and an inner circular HSS tube are abbreviated as square DTCCs in this paper unless otherwise specified. The experimental program included the FRP tube thickness, FRP tube width, and FRP type as the key test variables.

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